ACTN3 R577X polymorphism does not influence explosive leg muscle power in elite volleyball players

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We examined the association of R577X polymorphism (rs1815739) in the α-actinin-3 (*ACTN3*) gene with "explosive" leg muscle power performance in a group of male and female elite volleyball players ($n = 66$, 31 men, 35 women) and in a group of non-athletic male and female young adults ($n = 334$, 243 men, 91 women). We assessed power performance by means of the vertical squat and counter-movement jump tests. We also determined whether the genotypic frequencies of the *ACTN3* R577X genotypes differed between groups. We did not observe any effect of the *ACTN3* R577X polymorphism on study phenotypes in both groups, regardless of gender (all $P > 0.05$). Genotype frequencies were similar between volleyball and control groups ($P = 0.095$). Moreover, we did not find an association between the *ACTN3* R577X polymorphism and the likelihood of being an elite volleyball player using the dominant (RR vs RX+XX) and the recessive model (RR+RX vs XX). In summary, these findings suggest that the *ACTN3* R577X polymorphism does not influence explosive leg muscle power in elite volleyball players.

The expression of the skeletal muscle protein α-actinin-3 is almost exclusively restricted to fast twitch (type II) muscle fibers (Mills et al., 2001), where it constitutes one of the major components of the Z-disc. This protein also stabilizes their muscle contractile apparatus, which may confer a higher capacity for force absorption/transmission compared with slow (type I) subtype (Mills et al.,-2001). Moreover, it was speculated that α-actinin-3 promotes the formation of type II fibers through an interaction with the signaling protein calcineurin (Yang et al., 2003).

In the late 1990s, North et al. (1999) identified a C-to-T transition at nucleotide 1747 in exon 16 of the human α-actinin-3 (*ACTN3*) gene, which results in a stop codon (X) replacing the arginine (R) at amino acid 577 (R577X). The R577X variant results in two versions of the *ACTN3* gene in humans, a functional R allele and a null X allele. More than a billion people worldwide are homozygous for the R577X null allele (i.e. they have the XX genotype), and thus cannot express α-actinin-3 in their skeletal muscle fibers (MacArthur & North, 2004).

Studies in animal models (MacArthur et al., 2007, 2008) reported that the *ACTN3* knockout mouse (α-actinin-3 deficient) shows a decreased activity in the anaerobic glycolytic pathway and an increased activity in the aerobic oxidative pathway. Further, knockout mice also exhibit better fatigue resistance, decreased muscle mass and fiber diameter of fast (IIB) twitch muscle fibers, and reduced muscular strength (MacArthur et al., 2007, 2008). As for humans, Yang et al. (2003) showed that, at least in women, it is almost impossible to find an Olympic finalist (not to mention an Olympic champion) in "power" or "sprint" events such as jumping, throwing and 100 m running, with the *ACTN3* XX genotype. These findings were replicated in other studies with elite sprint/power athletes (Niemi & Majamaa, 2005; Papadimitriou et al., 2008; Roth et al., 2008; Santiago et al., 2008; Eynon et al., 2009; Massidda et al., 2009). In contrast, we recently reported the case of an elite male long jumper bearing the XX genotype who participated in two Olympic games, with a personal best performance of 8 m 26 cm, including an 8 m jump at the age of 17 (i.e. a better performance than Carl Lewis at the same age) (Lucia et al., 2007). Another example of a power-oriented athlete with the XX genotype is a Russian world record holder in hammer throwing (Druzhevskaya et al., 2008).

The effect of the *ACTN3* genotype has mainly been studied in elite athletes, due to the fact that the influence on muscle function will be most readily observable at the extremes of human performance. In

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this regard, besides technical and tactical skills, muscular strength and "explosive" leg power are the most important factors contributing to successful performance during elite volleyball competitions (Marques & Gonzalez-Badillo, 2006). α-actinin-3 is a determinant factor for producing high-power, high-velocity muscle contractions (MacArthur & North, 2004). As such, the *ACTN3* R577X polymorphism is a candidate gene to explain, at least partly, individual variations in volleyball performance.

In order to examine the effect of the *ACTN3* R577X polymorphism on the ability to produce peak ("explosive") power across the human performance continuum, we studied the association of the *ACTN3* R577X polymorphism with leg muscle explosive power performance in a group of male and female elite volleyball players and in a group of non-athletic male and female young adults. We also determined whether the genotypic frequencies of the *ACTN3* R577X genotypes differ between groups. We hypothesized that (i) the *ACTN3* R577X polymorphism is associated with jump performance in elite volleyball players, with the RR and RX genotype group having a better score than their XX counterparts and (ii) the XX genotype is underrepresented in the group of elite volleyball players.

Methods

Subjects

The present study comprised 334 (243 men, 91 women) healthy young adults (University students) and 66 (31 men, 35 women) elite volleyball players. All players belonged to the Spanish national team and competed at the international level, except 10 female players that were competing in the highest category at the national level. All participants were of the same Spanish (Caucasian) ancestry for at least three generations, and were free of any diagnosed cardiorespiratory disease. Participants from the control groups were physically active (Physical Education students), but were not engaged in competitive sports and performed less than one (power) or three (endurance) structured weekly training sessions within the last year.

Written consent was obtained from each subject. The study protocol was approved by the institutional ethics committee [*Universidad Europea de Madrid (UEM)*, Spain] and was in accordance with the Declaration of Helsinki for Human Research.

Genotype assessment

We extracted genomic DNA from saliva samples of university students (control group) and elite volleyball players during 2008. Our study followed the recommendations for the human genotype–phenotype association (Chanock et al., 2007).

Genotyping was originally performed during 2009 in the genetics laboratory of *Universidad Europea de Madrid* (Spain) following the methodology reported elsewhere (Lucia et al., 2006). In brief, the polymerase chain reaction (PCR) was performed in order to amplify the sequence containing the mutation. A fragment of 303 bp was amplified using the following primers: forward CTGTTGCCTGTGGTAAGTG GG, with 5′ VIC labeling, and reverse TGGTCACAGTATG CAGGAGGG. The PCR conditions were as follows: initial denaturing at 95 °C for 5 min; 35 cycles at 95 °C for 30 s, at 60 °C for 30 s, at 72 °C for 30 s and a final extension at 72 °C for 10 min.

ACTN3 genotypes (rs1815739) were established by enzymatic digestion of amplicons with *Dde I* (Lucia et al., 2006). The R577X change creates a restriction site resulting in fragments of 108, 97 and 86 bp. Digestion of R577 allele results in fragments of 205 and 86 bp. Digestion products (108 bp for 577X and 205 bp for R577) were detected by capillary electrophoresis in an ABI Prism 310 genetic analyzer (Applied Biosystems, Foster City, California, USA).

Phenotype assessment

We assessed the squat (SJ) and counter-movement jump (CMJ) tests using an infrared contact timing platform (Globus Ergo Tester, Codognè, Italy) to evaluate leg muscles' ability to produce "explosive" power (Young et al., 2001). Details of the methodology used to assess jump performance can be found elsewhere (Santiago et al., 2009a). In brief, the SJ tests were performed without rebound or previous counter movement. Subjects kept both hands on the hips and trunk straight before and during jumps. Before the jumps, they reached 90° of knee flexion angle for ~ 1 s and during jumps, they could not perform hip or knee flexions (Bosco et al., 1982, 1983). For the CMJ tests, subjects started from a standing position, with trunk straight, legs extended and both hands on hips and performed a vertical jump with a prior fast counter movement allowing 90° knee flexion (Bosco et al., 1982, 1983). During jumps, they kept both hands on hips, trunk straight and they could not perform hip or knee flexions.

Both tests were performed three times (each separated by a 2-min rest period) and the best score was retained. These tests have shown to be reliable (Santiago et al., 2009a). The participants were encouraged to do their best when performing the tests and were advised not to perform any strenuous physical activity within the previous 48 h. One-week before the tests, all the participants received comprehensive instructions on the tests, after which a familiarization session took place. All the tests were performed during 2008 under the supervision of the same researchers.

Statistical analysis

We performed the analyses with the Statistical Package for Social Sciences (SPSS, v. 16.0 for WINDOWS; SPSS Inc., Chicago, Illinois, USA), and the level of significance was set at $\alpha \leq 0.05$. We compared mean differences in the studied phenotypes between groups (control vs volleyball) using one-way analysis of variance. We analyzed the differences in the study phenotypes among *ACTN3* R577X genotypes in both the control and the volleyball group by regression analysis and one-way analysis of covariance after adjusting for weight, height and age.

We compared genotype frequencies between groups as wells as between men and women using the chi-square test. We used logistic regression to calculate the odds ratio (OR) for being an elite volleyball player using both dominant (RR vs RX+XX) and recessive (RR+RX vs XX) models.

Results

Characteristics of study participants by sex and group are shown in Table 1. Volleyball players

Table 1. Characteristics of study participants by sex and group

	Control			Volleyball			*P** all	*P** men	*P** women
	All	Men	Women	All	Men	Women			
Age (years)	21.0 (1.9)	21.1 (2.0)	20.5 (1.6)	20.4 (5.4)	18.2 (2.5)	22.3 (6.5)	0.125	**<0.001**	**0.017**
Weight (kg)	69.4 (10.7)	73.7 (8.6)	57.8 (6.4)	75.3 (11.6)	83.2 (10.5)	68.3 (7.2)	**<0.001**	**<0.001**	**<0.001**
Heigh (cm)	173 (8)	176 (6)	164 (6)	185 (9)	192 (6)	180 (6)	**<0.001**	**<0.001**	**<0.001**
SJ									
Flight time (s)	540.3 (51.3)	559.0 (39.8)	490.4 (45.0)	527.3 (107.1)	574.1 (45.0)	485.8 (127.9)	0.625	0.056	**0.006**
Vertical displacement of CG (cm)	36.1 (6.7)	38.5 (5.5)	29.7 (5.4)	35.5 (9.4)	40.6 (6.3)	30.9 (9.3)	0.511	**0.046**	0.392
CMJ									
Flight time (s)	551.6 (51.5)	570.8 (40.9)	500.3 (40.5)	566.8 (56.9)	602.3 (52.8)	535.3 (39.5)	**0.032**	**<0.001**	**<0.001**
Vertical displacement of CG (cm)	37.6 (6.9)	40.1 (5.8)	30.9 (5.0)	39.8 (8.1)	44.8 (7.89)	35.3 (5.4)	**0.026**	**<0.001**	**0.017**

Values are means (standard deviation). Bold numbers means statistically significant.

*P for group differences.

CG, center of gravity; CMJ, counter-movement jump.

were taller and heavier than individuals in the control group. Moreover, they performed better in the jump tests, which persisted after controlling for height (data not shown).

The association between the *ACTN3* R577X polymorphism and study phenotypes in both control and the volleyball groups is presented in Table 2. We did not observe any effect of the *ACTN3* R577X polymorphism on study phenotypes in either group. We repeated the analyses separately in men (Table 3) and women (Table 4) and the results did not change significantly.

The genotype distribution respected the Hardy–Weinberg equilibrium in the control group ($P = 0.595$), but not in the volleyball group ($P = 0.011$ for men and women together, $P = 0.092$ for men and $P = 0.059$ for women). Table 5 shows the genotype distribution of the *ACTN3* R577X polymorphism in the control and volleyball groups, the OR and the 95% confidence interval (CI) for being a volleyball player. We did not observe sex differences in the control ($\chi^2 = 2.910$, $P = 0.233$) or volleyball group ($\chi^2 = 0.078$, $P = 0.962$). Genotype frequencies were similar between volleyball and control groups. Moreover, we did not find an association between the *ACTN3* R577X polymorphism and the likelihood of being an elite volleyball player using the dominant or the recessive model. The results remained unaltered when the analyses were adjusted for sex, weight, height and age (data not shown) or when performed for men and women separately (Table 5).

Discussion

The present study indicates that the *ACTN3* R577X polymorphism is not associated significantly with the ability to produce peak ("explosive") power in elite volleyball players or in non-athletic people. We also observed that genotype frequencies were similar between volleyball and control groups. Taken together, these findings indicate that the *ACTN3* R577X polymorphism does not influence performance in explosive power-oriented sports such as volleyball.

These results were theoretically unexpected, given the role of α-actinin-3 on skeletal muscle phenotypes (MacArthur & North, 2004). Recent findings from association and case control studies are contradictory. Whereas several studies showed no effect of the *ACTN3* R577X polymorphism on muscular strength and power phenotypes (Moran et al., 2007; Delmonico et al., 2008; Walsh et al., 2008; McCauley et al., 2009; Santiago et al., 2009a), others reported an advantageous effect of the RR (Clarkson et al., 2005; Moran et al., 2007; Vincent et al., 2007) or the XX (Delmonico et al., 2007) genotype. Moreover, although a lower prevalence of the XX genotype was observed in sprint/power athletes (Yang et al., 2003; Niemi & Majamaa, 2005; Papadimitriou et al., 2008; Roth et al., 2008; Santiago et al., 2008; Eynon et al., 2009; Massidda et al., 2009), notable exceptions have been reported. For instance, we described the case of a Spanish elite long jumper (two times Olympian, personal best of 8.26 m), whose genotype for the *ACTN3* gene is 577XX (α-actinin-3 deficient) (Lucia et al., 2007). Druzhevskaya et al. (2008) reported that a Russian world record holder in hammer throwing had also the XX genotype.

McCauley et al. (2009) reported no influence of the *ACTN3* R577X polymorphism on the absolute or relative torque at high velocities, the twitch response, and the isometric strength of the knee extensors in Caucasian adult men. Similarly, Clarkson et al. (2005) reported no association between the *ACTN3*

Table 2. Mean (standard error) estimates of study phenotypes by genotypes of the *ACTN3* R577X (rs1815739) polymorphism in the control and the volleyball group

	Control			*P* add.	*P* dom.	*P* recess.	Volleyball			*P* add.	*P* dom.	*P* recess.
	RR ($n=104$)	RX ($n=169$)	XX ($n=61$)				RR ($n=14$)	RX ($n=43$)	XX ($n=9$)			
SJ												
Flight time (s)	542.4 (4.2)	543.0 (3.1)	532.8 (5.3)	0.223	0.680	0.090	529.9 (26.9)	532.0 (15.4)	500.0 (34.1)	0.198	0.241	0.402
Vertical displacement of CG (cm)	36.4 (0.6)	36.5 (0.4)	36.1 (0.7)	0.217	0.700	0.086	34.6 (2.2)	35.9 (1.2)	34.3 (2.8)	0.968	0.705	0.697
CMJ												
Flight time (s)	553.7 (4.2)	553.1 (3.1)	549.1 (5.2)	0.523	0.739	0.465	546.6 (12.4)	570.9 (7.1)	578.5 (15.7)	0.078	0.067	0.382
Vertical displacement of CG (cm)	37.9 (0.6)	37.8 (0.4)	37.3 (0.7)	0.547	0.758	0.487	36.9 (1.7)	40.4 (1.0)	41.2 (2.2)	0.090	0.068	0.441

Analyses were adjusted for sex, weight, height and age.

Add., additive; CG, centre of gravity; CMJ, counter-movement jump; dom., dominant (RR vs RX+XX); recess., recessive (RR+RX vs XX); RR, major allele; SJ, squat jump; XX, minor allele.

Table 3. Mean (standard error) estimates of study phenotypes by genotypes of the *ACTN3* R577X (rs1815739) polymorphism in men of the control and the volleyball group

	Control			*P* add.	*P* dom.	*P* recess.	Volleyball			*P* add.	*P* dom.	*P* recess.
	RR ($n=77$)	RX ($n=117$)	XX ($n=49$)				RR ($n=14$)	RX ($n=43$)	XX ($n=9$)			
SJ												
Flight time (s)	561.1 (4.7)	562.5 (3.6)	552.5 (5.7)	0.306	0.793	0.139	576.3 (14.5)	576.7 (8.4)	557.2 (19.8)	0.509	0.799	0.392
Vertical displacement of CG (cm)	38.8 (0.6)	39.0 (0.5)	39.6 (0.8)	0.324	0.828	0.143	40.9 (2.0)	41.0 (1.2)	38.2 (2.7)	0.469	0.750	0.342
CMJ												
Flight time (s)	572.8 (4.9)	573.1 (3.8)	569.5 (5.9)	0.707	0.909	0.602	597.3 (16.1)	606.1 (9.3)	592.5 (21.9)	0.972	0.786	0.680
Vertical displacement of CG (cm)	40.4 (0.7)	40.5 (0.5)	40.0 (0.8)	0.731	0.922	0.627	77.2 (2.3)	45.3 (1.3)	43.2 (3.2)	0.906	0.843	0.635

Analyses were adjusted for weight, height and age.

CG, center of gravity; CMJ, counter-movement jump; dom., dominant (RR vs RX+XX); recess., recessive (RR+RX vs XX); RR, major allele; SJ, squat jump; XX, minor allele.

Table 4. Mean (standard error) estimates of study phenotypes by genotypes of the *ACTN3* R577X (rs1815739) polymorphism in women of the control and the volleyball group

	Control			*P* add.	*P* dom.	*P* recess.	Volleyball			*P* add.	*P* dom.	*P* recess.
	RR ($n = 77$)	RX ($n = 117$)	XX ($n = 49$)				RR ($n = 14$)	RX ($n = 43$)	XX ($n = 9$)			
SJ												
Flight time (s)	494.6 (9.2)	492.4 (6.2)	480.1 (13.0)	0.429	0.737	0.823	518.3 (53.5)	487.3 (28.1)	433.4 (61.1)	0.746	0.680	0.928
Vertical displacement of CG (cm)	30.2 (1.1)	30.0 (0.7)	28.4 (1.6)	0.420	0.684	0.348	33.1 (3.9)	30.7 (2.0)	28.4 (4.5)	0.435	0.540	0.568
CMJ												
Flight time (s)	503.9 (8.2)	501.2 (5.6)	597.5 (11.7)	0.634	0.732	0.720	537.0 (14.2)	532.0 (7.5)	547.9 (16.2)	0.674	0.869	0.393
Vertical displacement of CG (cm)	31.3 (1.1)	30.9 (0.7)	30.5 (1.4)	0.649	0.725	0.711	35.4 (1.9)	34.9 (1.0)	36.8 (2.2)	0.704	0.905	0.461

Analyses were adjusted for weight, height and age.

CG, center of gravity; CMJ, counter-movement jump; dom., dominant (RR vs RX+XX); recess., recessive (RR+RX vs XX); RR, major allele; SJ, squat jump; XX, minor allele.

R577X polymorphism and isometric elbow flexor strength in men, yet they showed that women bearing the XX genotype had lower isometric strength than those with heterozygotes (RX). In a recent study, we also showed that the *ACTN3* R577X polymorphism was not associated with jumping (vertical SJ and CMJ tests) and sprint ability (30 m dash) in non-athletic men and women (Santiago et al., 2009a). Moreover, we did not observe significant differences on genotype frequencies between those with the best or the worst power performance (i.e. $\geq$ 90th vs $<$90th of the sex-specific percentile, respectively).

In contrast, Vincent et al. (2007) showed that healthy young men with the RR genotype had significantly higher relative dynamic quadriceps torques at 300°/s and a greater percentage of type IIX fibers than those with the XX genotype. Additional controversy stems from the fact that Delmonico et al. (2007) observed that the XX genotype was associated with higher knee extensor concentric peak power compared with RR and RX genotypes in adults aged ~65 years.

Naturally occurring jumping is a multi-joint movement that involves the coordinated participation of the majority of lower limb muscles (Ashley & Weiss, 1994; Brown & Weir 2001). During actual high muscle power actions (e.g. in team sport games), angular velocities at the hip or knee joints in the aforementioned actions can approach 800–1000°/s (Bosco et al., 1983). In this regard, the angular velocity in jump tests as those used in the present study is much higher than that of the phenotype tests applied in studies mentioned previously (Vincent et al., 2007; McCauley et al., 2009). In theory, a higher velocity may more effectively discriminate muscle function differences between genotypes.

Volleyball requires players to be fast and explosive (Marques et al., 2009). A high and quick vertical jump is a critical factor in performance, as is a powerful spike to shoot the ball with high velocity. In fact, a good vertical jump height often precedes an effective setup, block or spike. Given the key role of α-actinin-3 on muscular strength and power (MacArthur & North, 2004), theoretically, the *ACTN3* R577X polymorphism might help in explaining, at least partly, individual variations in volleyball performance-related phenotypes. The possibility of becoming an elite athlete depends on numerous factors, among which possessing a favorable genetic endowment cannot be discarded (Ruiz et al., 2009; Santiago et al., 2009b). However, muscle phenotypes (e.g. "explosive" power) are complex traits likely not reducible to a single polymorphism as the one studied here. It is likely that epigenetic factors, environment and the complex gene–gene and gene–environment interactions are also important determinants. Further, there might be other genetic var-

Table 5. Genotype distribution in control and volleyball groups

Genotype	Control		Volleyball		χ^2 (*P*-value)	OR (95% CI) dom.	OR (95% CI) recess.
	n	%	*n*	%			
All							
RR	104	31.1	14	21.2	4.717 (0.095)	1.680 (0.891–3.166)	0.368 (0.707–1.505)
RX	169	50.6	43	65.2			
XX	61	18.3	9	13.6			
p (R)		0.56		0.54	0.314 (0.314)		
q (X)		0.44		0.46			
Men							
RR	77	31.7	7	22.6	2.966 (0.227)	1.590 (0.657–3.850)	0.587 (0.196–1.755)
RX	117	48.1	20	64.5			
XX	49	20.2	4	12.9			
p (R)		0.56		0.55	0.019 (0.890)		
q (X)		0.44		0.45			
Women							
RR	27	29.7	7	20.0	1.211 (0.546)	1.687 (0.658–4.331)	1.097 (0.356–3.379)
RX	52	57.1	23	65.7			
XX	12	13.2	5	14.3			
p (R)		0.58		0.53	0.597 (0.440)		
q (X)		0.42		0.47			

CI, confidence interval; dom., dominant (RR vs RX+XX); OR, odds ratio; recess., recessive (RR+RX vs XX); RR, major allele, XX, minor allele.

iants not yet explored that could help to explain inter-individual variability in muscle phenotypes. Finally, beyond the genotype:phenotype association, the effect of micro-RNAs (miRNAs) on human muscle phenotypes remains to be determined (van Rooij et al., 2008).

The fact that in the power group genotype distributions did not meet the Hardy–Weinberg equilibrium must be kept in mind; yet, we believe it does not necessarily represent a major methodological limitation of our study. It is difficult to determine whether deviations from the Hardy–Weinberg equilibrium in this relatively small sample are due to genetic drift, migration (i.e. gene flow), mutation (e.g. change in the rate of mutation from the R to the X allele of *ACTN3* R577X polymorphism), selection or non-random mating. it should be noted that participants in the "control group" were physical education students, which may represent a selected population sample, yet their *ACTN3* R577X genotype frequencies (Table 5, RR: 31.1%; RX: 50.6%; XX: 18.3%) are very similar to those observed previously by us in 123 healthy, sedentary (non-physical education students) Spanish men (RR: 28.5%; RX; 53.6%; XX: 17.9%) (Lucia et al., 2006).

In summary, we did not observe an association between the *ACTN3* R577X polymorphism and "explosive" power performance in elite volleyball players or in non-athletic physically young adults of both genders. Moreover, the genotypic frequencies of the *ACTN3* R577X genotypes were similar between groups, suggesting that any influence of this polymorphism is not of a sufficient magnitude to influence jump performance in power athletes or in non-athletic Spanish Caucasian young adults.

Perspectives

α-actinin-3 is a sarcomeric protein that is almost exclusively expressed in fast muscle fibers, and seems crucial for producing fast and powerful contractions. The R577X variant results in two versions of the *ACTN3* gene in humans, a functional R allele and a null X allele. It was hypothesized that, at least among women, it is almost impossible to find an Olympic in "power" or "sprint" events, such as jumping, throwing and 100 m running, with the α-actinin-3-deficient (i.e. XX) genotype. This finding was replicated in a number of other studies, yet there are controversies, and there exist cases such as an Olympic-class long jumper with the *ACTN3* XX genotype. The present study showed that the *ACTN3* R577X polymorphism does not influence performance in explosive power-oriented sports such as volleyball. The possibility of becoming an elite athlete depends on numerous factors. It is worth nothing that muscle phenotypes (e.g. "explosive" power) are complex traits that are likely not reducible to a single polymorphism.

Key words: volleyball, squat jump, counter-movement jump, α-actinin-3, genotype.

References

Ashley CD, Weiss LW. Vertical jump performance and selected physiological characteristics of women. J Strength Cond Res 1994: 8: 5–11.

Bosco C, Mognoni P, Luhtanen P. Relationship between isokinetic performance and ballistic movement. Eur J Appl Physiol Occup Physiol 1983: 51: 357–364.

Bosco C, Viitasalo JT, Komi PV, Luhtanen P. Combined effect of elastic energy and myoelectrical potentiation during stretch-shortening cycle exercise. Acta Physiol Scand 1982: 114: 557–565.

Brown LE, Weir JP. ASEP procedures recommendation I: Accurate assessment of muscular strength JEPonline. 2001: 4: 1–21.

Chanock SJ, Manolio T, Boehnke M, Boerwinkle E, Hunter DJ, Thomas G, Hirschhorn JN, Abecasis G, Altshuler D, Bailey-Wilson JE, Brooks LD, Cardon LR, Daly M, Donnelly P, Fraumeni JF Jr, Freimer NB, Gerhard DS, Gunter C, Guttmacher AE, Guyer MS, Harris EL, Hoh J, Hoover R, Kong CA, Merikangas KR, Morton CC, Palmer LJ, Phimister EG, Rice JP, Roberts J, Rotimi C, Tucker MA, Vogan KJ, Wacholder S, Wijsman EM, Winn DM, Collins FS. Replicating genotype–phenotype associations. Nature 2007: 447: 655–660.

Clarkson PM, Devaney JM, Gordish-Dressman H, Thompson PD, Hubal MJ, Urso M, Price TB, Angelopoulos TJ, Gordon PM, Moyna NM, Pescatello LS, Visich PS, Zoeller RF, Seip RL, Hoffman EP. ACTN3 genotype is associated with increases in muscle strength in response to resistance training in women. J Appl Physiol 2005: 99: 154–163.

Delmonico MJ, Kostek MC, Doldo NA, Hand BD, Walsh S, Conway JM, Carignan CR, Roth SM, Hurley BF. Alpha-actinin-3 (ACTN3) R577X polymorphism influences knee extensor peak power response to strength training in older men and women. J Gerontol A Biol Sci Med Sci 2007: 62: 206–212.

Delmonico MJ, Zmuda JM, Taylor BC, Cauley JA, Harris TB, Manini TM, Schwartz A, Li R, Roth SM, Hurley BF, Bauer DC, Ferrell RE, Newman AB. Association of the ACTN3 genotype and physical functioning with age in older adults. J Gerontol A Biol Sci Med Sci 2008: 63: 1227–1234.

Druzhevskaya AM, Ahmetov II, Stratenkova IV, Rogozkin VA Association of the ACTN3 R577X polymorphism with power athlete status in Russians. Eur J Appl Physiol 2008: 103: 631–634.

Eynon N, Duarte JA, Oliveira J, Sagiv M, Yamin C, Meckel Y, Sagiv M, Goldhammer E. ACTN3 R577X polymorphism and Israeli top-level athletes. Int J Sports Med 2009: 30: 695–698.

Lucia A, Gomez-Gallego F, Santiago C, Bandres F, Earnest C, Rabadan M, Alonso JM, Hoyos J, Cordova A, Villa G, Foster C. ACTN3 genotype in professional endurance cyclists. Int J Sports Med 2006: 27: 880–884.

Lucia A, Olivan J, Gomez-Gallego F, Santiago C, Montil M, Foster C. Citius and longius (faster and longer) with no alpha-actinin-3 in skeletal muscles? Br J Sports Med 2007: 41: 616–617.

MacArthur DG, North KN. A gene for speed? The evolution and function of alpha-actinin-3. Bioessays 2004: 26: 786–795.

MacArthur DG, Seto JT, Chan S, Quinlan KG, Raftery JM, Turner N, Nicholson MD, Kee AJ, Hardeman EC, Gunning PW, Cooney GJ, Head SI, Yang N, North KN. An Actn3 knockout mouse provides mechanistic insights into the association between alpha-actinin-3 deficiency and human athletic performance. Hum Mol Genet 2008: 17: 1076–1086.

MacArthur DG, Seto JT, Raftery JM, Quinlan KG, Huttley GA, Hook JW, Lemckert FA, Kee AJ, Edwards MR, Berman Y, Hardeman EC, Gunning PW, Easteal S, Yang N, North KN. Loss of ACTN3 gene function alters mouse muscle metabolism and shows evidence of positive selection in humans. Nat Genet 2007: 39: 1261–1265.

Marques MC, Gonzalez-Badillo JJ. In-season resistance training and detraining in professional team handball players. J Strength Cond Res 2006: 20: 563–571.

Marques MC, van den Tillaar R, Gabbett TJ, Reis VM, Gonzalez-Badillo JJ. Physical fitness qualities of professional volleyball players: determination of positional differences. J Strength Cond Res 2009: 23: 1106–1111.

Massidda M, Vona G, Calo CM. Association between the ACTN3 R577X polymorphism and artistic gymnastic performance in Italy. Genet Test Mol Biomarkers 2009: 13: 377–380.

McCauley T, Mastana SS, Hossack J, Macdonald M, Folland JP. Human angiotensin-converting enzyme I/D and alpha-actinin 3 R577X genotypes and muscle functional and contractile properties. Exp Physiol 2009: 94: 81–89.

Mills M, Yang N, Weinberger R, Vander Woude DL, Beggs AH, Easteal S, North K. Differential expression of the actin-binding proteins, alpha-actinin-2 and -3, in different species: implications for the evolution of functional redundancy. Hum Mol Genet 2001: 10: 1335–1346.

Moran CN, Yang N, Bailey ME, Tsiokanos A, Jamurtas A, MacArthur DG, North K, Pitsiladis YP, Wilson RH. Association analysis of the ACTN3 R577X polymorphism and complex quantitative body composition and performance phenotypes in adolescent Greeks. Eur J Hum Genet 2007: 15: 88–93.

Niemi AK, Majamaa K. Mitochondrial DNA and ACTN3 genotypes in Finnish elite endurance and sprint athletes. Eur J Hum Genet 2005: 13: 965–969.

North KN, Yang N, Wattanasirichaigoon D, Mills M, Easteal S, Beggs AH. A common nonsense mutation results in alpha-actinin-3 deficiency in the general population. Nat Genet 1999: 21: 353–354.

Papadimitriou ID, Papadopoulos C, Kouvatsi A, Triantaphyllidis C. The ACTN3 gene in elite Greek track and field athletes. Int J Sports Med 2008: 29: 352–355.

Roth SM, Walsh S, Liu D, Metter EJ, Ferrucci L, Hurley BF. The ACTN3 R577X nonsense allele is under-represented in elite-level strength athletes. Eur J Hum Genet 2008: 16: 391–394.

Ruiz JR, Gomez-Gallego F, Santiago C, Gonzalez-Freire M, Verde Z, Foster C, Lucia A. Is there an optimum endurance polygenic profile? J Physiol 2009: 587: 1527–1534.

Santiago C, Gonzalez-Freire M, Serratosa L, Morate FJ, Meyer T, Gomez-Gallego F, Lucia A. ACTN3 genotype in professional soccer players. Br J Sports Med 2008: 42: 71–73.

Santiago C, Rodriguez-Romo G, Gomez-Gallego F, Gonzalez-Freire M, Yvert T, Verde Z, Naclerio F, Altmae S, Esteve-Lanao J, Ruiz JR, Lucia A. Is there an association between ACTN3 R577X polymorphism and muscle power phenotypes in young, non-athletic adults? Scand J Med Sci Sports 2009a: doi: 10.1111/j.1600-0838.2009.01017.x

Santiago C, Ruiz JR, Muniesa CA, Gonzalez-Freire M, Gomez-Gallego F, Lucia A. Does the polygenic profile determine the potential for becoming a world-class athlete? Insights from the sport of rowing. Scand J Med Sci Sports 2009b: 20: e188–e194.

van Rooij E, Liu N, Olson EN. MicroRNAs flex their muscles. Trends Genet 2008: 24: 159–166.

Vincent B, De Bock K, Ramaekers M, Van den Eede E, Van Leemputte M, Hespel P, Thomis MA. ACTN3 (R577X) genotype is associated with fiber type distribution. Physiol Genomics 2007: 32: 58–63.

Walsh S, Liu D, Metter EJ, Ferrucci L, Roth SM. ACTN3 genotype is associated with muscle phenotypes in women across the adult age span. J Appl Physiol 2008: 105: 1486–1491.

Yang N, MacArthur DG, Gulbin JP, Hahn AG, Beggs AH, Easteal S, North K. ACTN3 genotype is associated with human elite athletic performance. Am J Hum Genet 2003: 73: 627–631.

Young WB, MacDonald C, Flowers MA. Validity of double- and single-leg vertical jumps as tests of leg extensor muscle function. J Strength Cond Res 2001: 15: 6–11.